BLAST WAVES GENERATED BY ACCIDENTAL EXPLOSIONS

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As a basis for the discussion of the blast waves produced by accidental explosions the structure of the blast wave from an ideal explosion and the mechanisms by which such a blast wave produces damage will be discussed. Next, some general results concerning the manner in which nonideal source behavior produces nonideality of the blast wave will be presented with examples. Finally, accidental explosions will be grouped into nine different types depending upon the nature of the source behavior during the explosion and the events that lead up to the explosion. The nature of the blast wave produced by each of the different types of accidental explosions will then be discussed with examples as appropriate to illustrate how the mechanisms involved in accidental explosions affect the blast waves produced by these explosions.

INTRODUCTION

In the past 10 to 15 years there has been a considerable increase of interest in accidental explosions of all types and the hazards they pose to structures and people in their immediate vicinity (1). This increased interest has led to a considerable amount of activity to characterize the nature of the various accidental explosion processes that can occur and the danger associated with internal explosions, the production of primary and secondary fragments, radiation damage from a fireball and last, but not least, the blast wave produced by the explosion (2). This paper will focus on our current understanding of source behaviors that lead to nonideal blast waves as well as the nature of the blast waves produced by various types of accidental explosions.

IDEAL BLAST WAVES

All free field blast waves whether ideal or not are simple waves traveling away from the source region. Point source, nuclear or bare charge spherical high explosive explosions all produce blast waves which have essentially the same structure at distances from the source where the maximum pressure in the wave is less than about 100 atmospheres (3). These "ideal" waves consist of a lead shock wave followed by a rarefaction fan which causes the pressure to fall slightly below the ambient pressure before it rebounds to the initial atmospheric pressure. Since the wave is simple the

flow associated with the wave is uniquely related to the local pressure in the wave. Specifically, the flow is outward when the pressure is higher than ambient and inward when the pressure drops below ambient.

The three properties of an ideal wave which cause damage are the maximum overpressure, the positive impulse I_+ where $I_+ = \int P dt$ from the time when the shock arrives until the pressure first returns to ambient and the flow velocity associated with the wave (2). Sachs (4) showed theoretically and it has been verified experimentally (5) that the first two of these three properties scale to an energy scaled radius. Specifically, at any distance from the source, R, the quantities $\bar{P} = (P_s - P_o)/P_o$ and $\bar{I} = (I_+ a_o)/(E^{1/3} P_o^{2/3})$ scale to $\bar{R}$ where $\bar{R} = R/R_o$ and $R_o = (E/P_o)^{1/3}$. Here E is the total energy of the source and P_o is the local atmospheric pressure.

The mechanism by which a structure is damaged by a blast wave is different for each of the three properties described above. If the duration is very long compared to the response time of the structure, the structural elements are deflected to about twice the extent that they would be if the pressure (now a reflected shock pressure) were applied statically. In this case the strain energy in the structure can be equated to the potential energy stored by the deflection and damage occurs when this amount of energy is sufficient to cause plastic flow and therefore permanent deformation. If the duration is very short relative to the characteristic response time of the structure, the impulse of the wave determines the amount of kinetic energy imparted to the structural elements and this kinetic energy can be equated to the strain energy that will ultimately be stored in these elements. In this impulsive limit the overpressure in the shock has no effect on damage (6).

The third damage mechanism is related to a drag force which first arises because it takes a finite amount of time for the shock wave to reflect, refract and engulf the body and then continues because the body is immersed in a high velocity flow field. Structures that are particularly vulnerable to this type of damage are light standards or unattached bodies like trucks or people. In the latter case, damage is caused by tumbling or gross displacement (2).

NON-IDEAL BLAST WAVES

Most accidental explosions generate a blast wave whose structure is different from the structure of an ideal blast wave. Theoretical, numerical, and experimental work has shown that the differences are directly related to the way that energy is added to or initially distributed in the source region. To illustrate the differences three example spherical source regions will be considered. These are an idealized bursting sphere, the ramp addition of energy (representing a spark) and spherical deflagrative and detonative addition of energy. Additionally, there will be a brief discussion of the effects of non-spherical deflagration in a source region.

The burst of a pressurized frangible sphere containing an ideal polytropic gas has been studied numerically (7) and experimentally (8). All the numerical calculations described here (including that for bursting spheres) used a one dimensional finite difference artificial viscosity computer program in spherical coordinates to follow the flow associated with specific source behaviors (9). For the bursting sphere studies the calculation was started with the source region at a series of high pressures and different temperatures. It was found that when the energy in the sphere was calculated using Brode's (10) formula, $E = (P_s - P_o) V/(\gamma - 1)$, where V is the sphere volume and γ is the heat capacity ratio of the polytropic gas in the sphere, the sphere bursts produced a blast wave whose pressure was never larger than

that calculated using the shock tube bursting pressure equation and decreased monotonically as the shock propagated away from the source. Furthermore, for high pressure sphere bursts the shock pressure asymptotically approached the energy scaled overpressure curve for a high explosive charge. However, for sphere pressures less than about 6 P_o, the shock overpressure curves did not reach but paralleled the high explosive curve. In other words, far field equivalency in overpressure was lost.

Two other general behaviors of the blast wave from a bursting sphere are 1) positive phase impulse always scales with source energy using Sachs' scaling (this is generally true for all spherical non-ideal explosions) and 2) the negative phase impulse for spheres with low energy density (i.e., with internal pressures below about 100 atmospheres) is always very large when compared to the negative phase for an ideal blast wave. It is in fact more than one half of the positive phase impulse. Furthermore, this negative phase is followed by a relatively strong shock wave whose amplitude is approximately 1/3 of the amplitude of the initial shock in the blast wave. This is illustrated in Figure 1 which is experimental data obtained from a bursting frangible sphere. A complete set of pressure distance curves for a number of equally spaced times after sphere burst is shown in Figure 2. Notice from Figure 2 the large rarefaction fan propagating to the center, the very large pressure spike produced at the center, and the second shock propagating away from the center. Brode and Chou et al (11) showed many years ago that an extended source such as a bursting sphere exhibits this behavior.

It was also observed that the dimensionless overpressure-scaled distance curves for the different initial sphere conditions paralleled each other when plotted against $\bar{R}$. Furthermore, dimensional analysis showed (8) that for idealized sphere bursts one must know the sphere source energy, E, the sphere pressure, P_s/P_o, the internal velocity of sound of the gas in the sphere relative to that of the surroundings, a_s/a_o, and the heat capacity ratio, γ, of the gas in the sphere to uniquely determine the initial shock pressure and sphere radius on a ($\bar{P}$, $\bar{R}$) plot. With this information the ($\bar{P}$, $\bar{R}$) nomograph that has been constructed can be used to determine the blast wave overpressure produced by any idealized bursting sphere (7).

Numerical calculations have been performed to study the ramp addition of energy (12). In this case, energy is added in a spatially uniform manner to the entire source region at a rate which is growing exponentially with time until the maximum amount of energy is added. Figure 3 shows that in this case a compression wave is first generated which steepens into a shock wave some distance from the source. Figure 3 also shows the effect of finite source size, because it clearly shows the rarefaction fan propagating towards the center of the source region as energy is being added to the source region. A systematic study of the effect of energy density (defined at E/C_vT_o) and dimensionless time of energy addition (defined as a characteristic time for energy addition divided by a characteristic acoustic transit time for the source region, $t_a = r_o/a_o$ where r_o is the initial radius of the source region and a_o is the initial velocity of sound in the source region) was performed. This showed that, irrespective of the nonideal behavior of the blast wave close to the source region, source regions which had both a high energy density and a very short dimensionless rate of heat addition exhibited far field equivalency in overpressure and produced a blast wave which was indistinguishable from that produced by an ideal source. However, when energy density dropped to about 8 or 9, and dimensionless rate of energy addition increased to about unity, far field equivalency in overpressure was lost. In other words, the overpressure scaled distance curves were all below those of an ideal explosion with the same total source energy. As in the case of bursting sphere the far field positive impulse was equivalent to that

of an ideal wave on an energy scaled basis.

Numerical (13) and experimental (14) studies have been performed on the blast wave propagating away from a centrally ignited deflagrative or detonative explosion of a gas mixture initially at ambient pressure (15). The calculations have shown that at a radius of about three times the actual combustible sphere radius, the blast wave becomes equivalent to that produced by an ideal explosion, if the initial explosion is centrally ignited and is either detonative or deflagrative with a normal burning velocity of more than approximately 1/8th of the initial velocity of sound. These calculations also show that when the burning velocity drops to approximately 1/16th of the initial velocity of sound, far field overpressure equivalency is lost and the blast wave no longer contains a lead shock wave but instead consists of a simple compression wave propagating away from the source region. This is shown in Figure 4. For lower burning velocities than this, the overpressure in the wave is extremely low and can be modeled by using an adaption of Taylor's (16) original analytical solution for the blast wave produced by a sphere expanding at constant velocity. This behavior is shown in Figure 5.

The blast wave produced by low velocity deflagrative combustion of a non-spherical source has also been studied (17). In this case the acoustic principle first enunciated by Stokes (18) in 1849 has been applied by assuming that the deflagrative combustion can be treated as a monopole source of very low frequency.

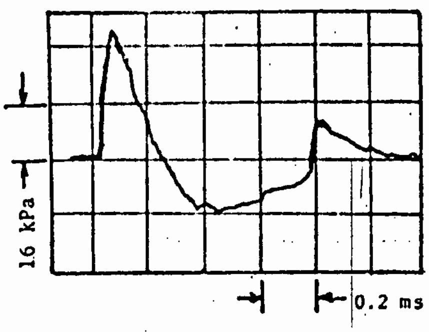

Figure 1

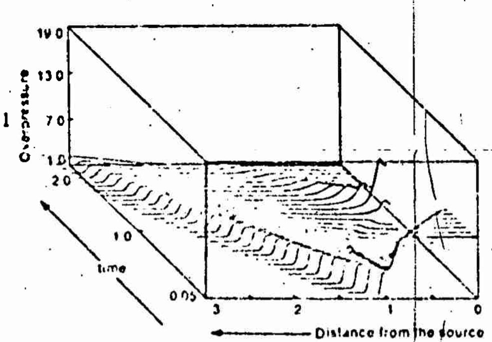

Figure 2

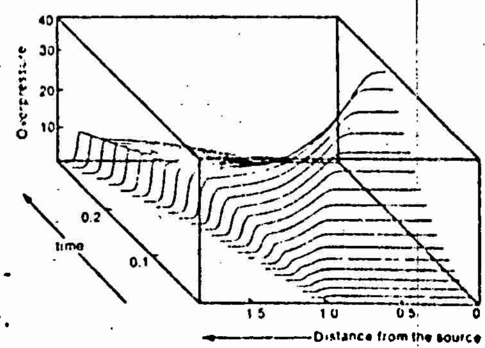

Figure 3

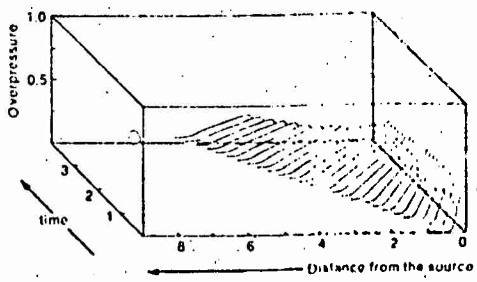

Figure 4

NOTE: Figure captions are at the end of the paper.

When this is done, one finds that the maximum overpressure that one can obtain from deflagrative combustion is a function of the aspect ratio of the source region and decreases very rapidly with increases in aspect ratio. This is shown in Figure 6. This theoretical observation has been verified by experimental studies in which combustion of a spherical soap bubble was initiated near the edge (19). In this case, the acoustic overpressure was considerably lower than the acoustic overpressure when the soap bubble was initiated centrally. The reason why this is true is that in spherical coordinates the maximum overpressure occurs when the product of the burning velocity and flame area exhibit the maximum rate of increase. The theory yields the conclusion that no overpressure is generated in spherical coordinates by a flame of constant area which has a constant burning velocity.

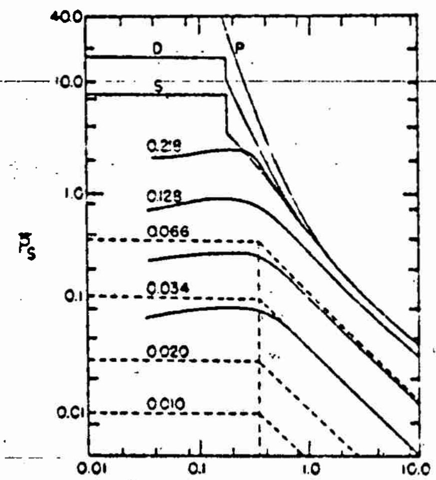

Figure 5

ACCIDENTAL EXPLOSIONS

When accidental explosions are classified by source behavior, one finds that there are nine major types that can occur (1). These are:

1. condensed phase detonations.
2. combustion explosions of gaseous or liquid fuels in enclosures.
3. combustion explosions of dusts in enclosures.
4. boiling-liquid-expanding-vapor-explosions (BLEVEs).
5. unconfined vapor-cloud explosions.
6. explosions of pressurized vessels containing non-reactive gases.
7. explosions resulting from chemical reactor runaway.
8. physical vapor explosions.
9. explosions resulting from nuclear reactor runaway.

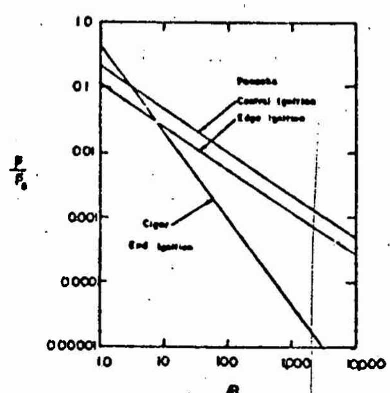

Figure 6

The blast waves that are generated by each of these different types of explosions are quite dependent on source behavior and therefore, are different from explosion to explosion. Some general statements can be made, however. In the following each type of explosion will be discussed separately.

Condensed phase detonations produce a blast which is nearly ideal based on the total energy that is available from the source region. If there is considerable confinement, one must take into account the energy impart to the confinement by the explosion and if the explosion occurs at ground level (most do), the energy involved in cratering must be included. Ground level

reflection with no cratering would cause the blast wave to appear as if the explosive energy were twice the actual amount of explosive involved. With cratering the usual multiplying factor is taken to be 1.8 (3).

Combustion explosions of gaseous or liquid fuels in enclosures show two distinct limit behaviors. If the enclosure has a low length to diameter ratio ($L/D \leq 6$) and if there are not too many obstacles in the path of the flame, the pressure rise in the enclosure will cause the enclosure to relieve itself at a relatively low overpressure. For example, buildings will fail at 2 to 3 psi overpressure whereas the explosion, if allowed to run its course, would generate at least 90 psi. Under these circumstances, the building is usually completely destroyed by the explosion but pieces are not thrown very far. Also because the source pressure never gets very high the blast wave is minimal. Generally speaking, people close to the source do not hear a blast wave in this case. They simply feel an impulsive flow of air as the explosion process displaces the atmosphere around the explosion source. In the other limit case, when the L/D is large, or when there are many obstacles in the path of the combustion wave, turbulent boundary layer growth and eddy shedding cause flame accelerations to occur which can lead to generation of pressure waves and shock waves in the enclosure. In severe cases the acceleration will be violent enough to actually cause the flame system to make a transition to detonation. In this limit case damage is localized but very severe. Fragments can be thrown large distances and the blast wave that is produced can be quite intense. These are, however, extended source volume explosions (i.e., they have a low energy density) and therefore the blast waves from this source always exhibit a strong negative phase. Because of this it is quite common to see negative phase damage on structures that are close to the source region, when this type of explosion occurs.

Combustion explosions of dusts in enclosures have the same L/D limit behaviors as a combustion explosion of vapors and gases in enclosures and the blast waves that are produced by such explosions are of the same type as those produced by explosions of gases or liquid fuels in enclosures. There is a difference, however, in the way that these explosions occur inside the enclosure. In order for a dust to form a combustible mixture in air, the extinction coefficient of the suspended dust relative to light transmission must be of the order of 30 cm. This is such a high concentration of airborne dust that it could not be tolerated on a continuous basis in the work place. Nevertheless, disasterous secondary explosions do occur in industries that handle organic or metal dusts. These always occur because the work place was allowed to become quite dirty and a primary explosion in a piece of equipment produces a large external fireball and air motion ahead of it which picks up the dust in the work place and propagates the explosion throughout the work place.

Boiling-liquid-expanding-vapor-explosions (BLEVEs) (20) occur when a ductile tank containing a flash evaporating liquid at high pressure is heated externally until the tank tears open. The blast wave in this case is usually not considered to be dangerous. It has been shown experimentally that a bulk quantity of flash evaporating liquid when suddenly exposed to atmospheric pressure evaporates so slowly that the evaporation process cannot contribute to the blast wave (21). Therefore in this case, the blast wave arises only from the vapor space above the liquid in the tank. In this case the maximum blast wave strength can be estimated if one knows the size of that vapor space and treats the explosion as a bursting sphere with the vapor space volume and initial pressure. The real danger in BLEVEs is 1) the flash evaporating liquid can cause rocketing of pieces of the tank to large distances and 2) if the contents of the tank are combustible and catch on fire immediately, a large fireball can be produced, which can injure and kill people by radiation and start new fires some distance from the original fire.

Unconfined vapor-cloud explosions occur when there is a massive release of a combustible hydrocarbon in the atmosphere with delayed ignition (22) (ignition delays from 15 seconds to 30 minutes are common with this type of accident). In this case a large cloud of combustible mixture of the fuel with air is formed and ignition can either lead to a very large fire or a very large fire plus an explosion which causes a damaging blast wave to form. There is mounting evidence that a damaging blast wave occurs only if the initial flame propagation process accelerates until either rapid volumetric combustion or some sort of supersonic combustion or possibly detonation occurs. Recently, it has been shown that one can produce transition to detonation without heating the combustible mixture to the autoignition temperature (23). All that is needed is a sufficiently large hot gas-cold gas mixing region in a flame jet. Furthermore, the acoustic theory for high aspect ratio source regions shows quite conclusively that deflagrative combustion as such cannot produce the damaging blast waves that have been observed as the result of vapor cloud explosions (17).

Explosion of pressurized vessels containing nonreactive gaseous materials produce blast waves which can be treated in a rather straightforward manner using the bursting sphere formulas that were discussed above. One can always assume in this case that the bursting sphere formula will yield the maximum overpressure that one could expect. This is because virtually all pressure vessels are made of ductile material and ductile vessels tear only slowly once failure starts. Thus the high pressure gas will be released at a slower rate than if the vessel were a frangible vessel. If the vessel is frangible there are ways to estimate kinetic energy imparted to the fragments and this energy should be subtracted from the total stored energy in the vessel to estimate the blast wave structure using the bursting sphere formulas described above.

Explosions resulting from chemical reactor runaway occur frequently in the chemical industry. They are due primarily to the fact that the exothermic reaction that is being carried out in the vessel occurs too rapidly either because too much catalyst has been added to the system or because the cooling system for the vessel fails. In either case, the pressure in the vessel rises rather rapidly and if the vessel is not adequately vented, the vessel explodes. In many cases these are ductile tears and the explosion can be assumed to be a BLEVE. In most cases the blast wave, as such, is not severe, but damage to the local environment is because of the fragments that are produced and the danger of a major fire following the explosion.

Physical vapor explosions occur when a hot liquid or solid contacts a cold liquid and causes very rapid vaporization of the cold liquid (24). These explosions occur in the steel and aluminum industry where water is the cold liquid and during the spill of liquid natural gas where water is the hot liquid. They can be quite severe. However, the blast wave that they generate is nonideal because of the extended size of the source region. There has been no experimental study of the structure of the blast wave produced by physical vapor explosions.

Explosions resulting from nuclear reactor runaway fortunately have not yet occurred. A nuclear reactor runaway cannot generate anything like a nuclear bomb detonation. However, it can pressurize the containment vessel to such a pressure that the vessel will burst, releasing its contents to the outside atmosphere. In this case, the discussion of the blast wave and the damage it produces would be moot because the release of long range radio-active material would represent a much more serious catastrophe.

SUMMARY AND CONCLUSIONS

It has been shown that high energy density and high power density sources

produce "ideal" blast waves whose structure is related only to the total energy of the source region. It has also been shown that low energy density or extended sources and sources in which the energy is added slowly produce nonideal blast waves whose primary deviation from ideality is the lack of far field equivalency in overpressure. It has also been shown that these waves contain a large negative phase following the initial positive phase and that this negative phase is followed by a relatively strong second shock. Interestingly, both theory and experiment have shown that for a spherical source region, positive impulse is always predicted by simple energy scaling, irrespective of how nonideal the source behavior is.

Additionally, accidental explosions have been catagorized into nine types, primarily based on the behaviors of the source regions during the explosion process itself. The nature of the blast wave produced by each of these nine types was discussed briefly.

It appears that we currently have sufficient information to either evaluate the potential explosion hazard of any specific situation or to evaluate the nature and course of the explosion after such an incident has occurred. Furthermore, since the principles of blast resistant design are now well understood, such design is being used more and more frequently in locations where the potential for an explosion exists.

It appears that the most important avenue for new research relative to the blast wave from accidental explosions is to study in some systematic manner the effect of the explosion of highly nonspherical source regions on the blast wave produced in the surroundings.

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Figure Captions

Fig. 1 An oscilloscope trace of the free field blast wave from a bursting sphere containing air P_s = 52.5 Atm. $\overline{P}$ = 0.40, $\overline{R}$ = 0.69.

Fig. 2 The blast wave produced by a sphere initially at 9 Atm. pressure.

Fig. 3 The blast wave produced by the ramp addition of energy.

Fig. 4 The blast wave produced by a centrally ignited low velocity flame.

Fig. 5 Scaled overpressure, $\overline{P}$, versus energy scaled radius, $\overline{R}$, for detonation (curve D) bursting sphere (curve S) and various centrally ignited flames. Curve P is for Pentolite (ideal wave). Numbers given on the curves are the ratio S_u/a_o where S_u is the assumed normal burning velocity and a_o is the initial velocity of sound. The solid lines (except for Pentolite) are the result of numerical calculations. The dashed lines were obtained by using Taylor's analytical solution for an expanding sphero, suitably modified to replace the sphere by a propagating flame. Note the good agreement with theory at S_u/a_o = 0.066 and 0.034.

Fig. 6 Effect of the aspect ratio, $\mathcal{R}$, on the maximum blast wave pressure rise for the deflagrative combustion of pancake and cigar-shaped clouds. Cloud volume, normal burning velocity and observer distance from cloud center are all assumed to be constant from cloud to cloud.

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